HAZARDOUS MATERIAL

HAZMAT TRANSPORTATION SAFETY

Of the 210,000 tank cars in the North American freight car fleet, nearly one-half carry materials that are flammable, corrosive, poisonous, or pose other hazards. About 1 million shipments of hazardous materials (hazmat) are made via tank cars each year.

Tank car safety research is conducted by the FRA, partially in a cooperative effort with the Association of American Railroads/Railway Progress Institute (AAR/RPI) Tank Car Committee. FRA-sponsored research focuses on problems related to fatigue, fracture, and welding in the current tank car fleet, as well as on improving standards and procedures for future tank car design.

Reliability of Tank Car Fleet

The reliability of a tank car may be defined as the probability that, when operating under stated environmental conditions, the tank car will perform its intended function adequately for a specified interval of time. Although complete and catastrophic failure is easily recognized, the integrity of the tank car for the purpose of safe packaging for hazardous materials can deteriorate gradually over time. To avoid catastrophic failures, it is essential that potentially unsafe conditions are recognized and remedied before a failure results. To achieve this objective, the behavior of safety critical components, under both normal and extreme conditions, must be considered.

Knowing the reliability of each tank car is the key to preventing catastrophic failures. However, reliability is a function of many design and operating variables. A methodology to account for the effect of these variables on reliability is being developed. Accurate reliability assessments will provide tank car owners with the quantitative information needed to determine safe and cost-effective inspection and maintenance procedures, which help to ensure the safe transport of hazardous materials.

The work being conducted to develop the methodology for determining and improving tank car reliability includes characterizing the service environment for tank cars, determining the behavior of tank cars under normal service conditions, and extreme conditions, such as derailments. Specific programs to investigate these issues are described in the following sections.

Characterization of Lading and In-Service Environment Loadings

Tank Car and Tank Car Lading Compatibility - The objective of the tank car and tank car lading compatibility project is to develop a process to ensure that lading is carried in tank cars that are compatible with safety requirements of the lading. For example, the thermodynamic properties of some materials, such as methacrylate monomers, can cause excessive pressures when the tank car is exposed to fire. It is important that tank cars carrying such materials have pressure and vent capacity to accomodate this high-temperature behavior. The tank car and tank car lading compatibility project examined a wide range of lading materials for specific safety requirements and has developed new guidelines for lading-specific tank car requirements.

Designing Normal Service and Extreme Service Forces Into Tank Car Structural Integrity - A few incidents of tank car structural damage and failure have occurred without prior warning to train operators; i.e., under completely “normal” operating conditions. As a result, the tank car industry is currently studying the use of damage tolerance analysis (DTA) to provide continued tank car integrity. The aim of damage tolerance methodology is to accurately predict the growth of potential flaws in a structural system, so that parts are inspected and, if necessary, repaired or replaced before any flaws become critical. To incorporate this approach into the tank car industry, an improved understanding of the in-service loads (load spectrum) experienced by tank cars is needed.

The goals of this research project are 1) determine the loads experienced by tank cars under normal service conditions, 2) determine the loads experienced by tank cars under severe loading conditions (e.g. coupling at excessive speeds), and 3) use these loads to design mechanical tests to simulate actual tank car service under controlled, laboratory conditions.

Currently, there exists a load spectrum, given in Chapter 7 of the Association of American Railroads Manual of Standards and Recommended Practice, known as the Freight Equipment and Environmental Sample Test (FEEST), which is used to represent service conditions for freight cars in laboratory and numerical simulations. However, there are some questions regarding how well FEEST represents the loads encountered by tank cars. Data from completed research has been used to develop a load spectrum that is more representative of loads experienced by tank cars. The new spectrum has been used to design mechanical tests that represent the service environment of tank cars.

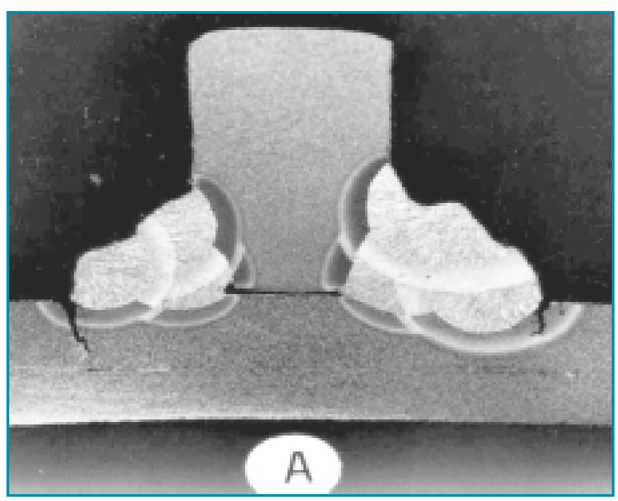
Similar research is needed for forces and impacts experienced in accident scenarios. These data have not been compiled for ready reference, and might not exist at all. These data are required to validate critical flaw size calculations. Data will be gathered from literature, industry data bases, and from application of engineering principles. It is anticipated that this dataset will evolve over time.

Behavior Under Normal Conditions

Determination of Critical Flaw Size in Tank Cars - The development of viable guidelines for critical flaw sizes in tank car components is critical to the application of damage tolerance analysis for the safe operation of tank cars. Every component of a tank car has a critical flaw size - the crack size for which failure is likely under operational loads. Critical flaw sizes must be known for all fatigue sensitive locations to define non-destructive testing performance criteria and intervals. To determine critical flaw sizes, both the stress state and material behavior of a tank car components must be well understood.

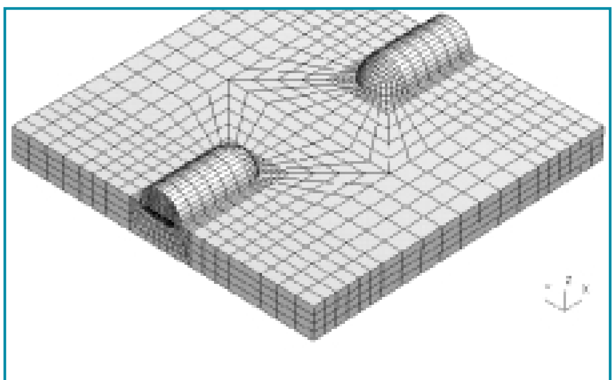
Recent work in the areas of structural integrity - including fracture-mechanics-based DTA of tank car stub sills - exposes a need for a compilation of past testing to catalog the range of known material properties, and to define additional work necessary to document fracture toughness (the ability of a material to resist cracking). In recent years, investigations have shown that fracture toughness is a strong function of specimen geometry. This dependence makes it difficult to predict large-scale structural behavior based on the results from small scale laboratory tests results. Further research is required to incorporate state-of-the-art theories on fracture initiation and propagation into finite element models for tank car damage evaluation.

Residual Stresses and Welding Practices - Premature failure of tank car shells in tank cars containing hazardous materials poses a significant threat to public safety and the environment. A significant number of cracks that occur in the shells of railroad tank cars are near welds. A cross section of a welded skin/stiffener detail is shown below. Small cracks can be seen near the boundaries of the welds. The development and growth of these cracks are affected by residual stresses that are induced by the welding process. Understanding these changes will help to develop recommendations for improved welding practices, inspection strategies, and inspection frequencies to avoid catastrophic failure or leaks in tank cars.



A research project is underway to develop the capability to numerically predict residual stresses associated with welding procedures. Results from preliminary analyses indicated that significant tensile residual stresses, which would encourage the formation and growth of fatigue cracking, could be expected in the tank car shell near the ends of skip welds.

Laboratory specimens with skip welds were fabricated by the Oregon Graduate Institute (OGI). The configuration of these specimens consists of a pair of skip welds that have been laid on a plate of conventional shell material. These laboratory specimens were used to determine residual stresses resulting from the welding process, using a destructive technique known as blind hole drilling. Further confirmation of the residual stress state resulting from welds was obtained by blind hole drilling measurements at the ends of skip welds in actual tank car shells. However, the techniques used for these tests are not capable of determining the through-the-thickness residual stress gradients caused by the welding process. In 1994, the National Institute of Standards and Technology (NIST), under a reimbursable agreement with the DOT, conducted additional measurements using the laboratory specimens remaining from the OGI project. In this case, the through-the-thickness distribution of residual stress was estimated non-destructively by means of a combination of x-ray and neutron diffraction measurements.



In 1995, in support of the FRA, the Volpe Center began to develop the methodology to perform 3-dimensional, thermo-mechanical, elastic-plastic finite element analyses to predict the through-the-thickness distribution of residual stresses produced by welding. Accurate geometric models of the specimens tested by NIST were used, so that the numerical results could be validated by comparison to experimental results. A typical mesh is shown in the accompanying figure.

The procedure to numerically predict the residual stresses in the tank shell involves simulation of the cooling of the hot weld bead on the cooler base plate. During this process, the bead shrinks on the stiffer plate. The resistance of the plate to shrinking causes stresses to develop. Preliminary results from the finite element modeling were published as part of the proceedings from the 1997 IEEE/ASME Joint Railroad Conference. The general agreement between the numerical simulation and the experimental measurements illustrates the viability of the analysis methodology. Future work will involve using the validated methodology to investigate the sensitivity of residual stresses to parameters that can be controlled by design or shop practice, thereby improving future welding practice.

Behavior Under Extreme Conditions

Puncture Resistance of Tank Cars - Scale model and full scale puncture velocity tests conducted in the 1970s and early 1980s led to regulations for head shields for tank cars carrying certain hazardous materials. Further tests on tank cars made of aluminum and tank cars designed for transporting chlorine were performed in the mid-1980s. Research sponsored by the AAR/RPI developed a set of semi-empirical equations to predict the velocity at which tank car shells, both with and without head protection, would puncture.

In previous research sponsored by the AAR/RPI, a set of semi-empirical equations was developed to determine the velocity at which puncture of the shell, with and without head protection, would occur. In research sponsored by the FRA in 1996, the general applicability of these equations was examined by comparing results from the equations to puncture data available in the open literature. A recent FRA research project used the existing set of experimental data to evaluate the semi-empirical equations for puncture velocity. Predictions from the semi-empirical equations for puncture velocity are within reasonable agreement with experimental data. The agreement between predictions and experimental data becomes worse, however, when shield protection is present and when the tank is internally pressurized. In cases involving shield protection, the calculated puncture velocity tends to be conservative (lower than the observed test cases). More detailed computational models, based on finite element analysis, are being developed to predict the puncture velocity of tank car shells. These models will enable more efficient design of shield protection, and to predict the effects of pressurization on tank car behavior in accident scenarios.

Tank Car Damage Assessment - Emergency responders must make on-the-spot decisions regarding the best course of action to follow in the aftermath of an accident. These decisions must be made in a timely manner and, therefore, are often without the benefit of either complete information or a detailed analysis. A tank car accident in Waverly, Tennessee in the 1970s resulted in the death of a number of emergency responders when a tank car ruptured unexpectedly. The tank car had an undetected crack that grew over several days and caused the disaster. The AAR's Bureau of Explosives has developed a set of guidelines to protect emergency personnel when responding to hazardous materials accidents. These guidelines are derived from the opinions of technical experts, and based on visual inspection of the accident scene. The current emergency response guidelines are being reviewed for adequacy, timeliness, and accuracy, to ensure that emergency responders can make field decisions based on the best technology and information available. These guidelines will be updated periodically when new technologies emerge.

Development of Next Generation Tank Car Fleet

Improvements in materials, materials processing, and damage tolerant design methodology will lead to improved cost effectiveness and reliability for the next generation of tank car designs. The FRA is sponsoring and performing research to improve the understanding of the effects of manufacture, processing, geometry, and service loads on the behavior of materials in use in tank cars. New materials and materials processing are discussed in the following sections.

Tank Car Steels - Materials under consideration for tank car construction require certain minimum mechanical properties. This project will develop an efficient procedure whereby potential materials for tank car construction can be identified based upon mechanical behavior. A report will be prepared to include all prior and current work in this area.

Improved Manufacturing Practices - Shell materials with improved fatigue and fracture resistance properties can be utilized to improve the next-generation hazmat tank car fleet. In 1994, the FRA began studies to explore the possibilities of producing economical, fracture-resistant plate stock for tank car shells. The microstructure of standard carbon steel is pearlite. Uniform microstructure consisting of carbide-free bainite could lead to improved performance of tank car shells.

The automotive industry currently uses a process known as thermo-mechanically controlled processing (TMCP) to produce sheet products (0.1-inch thick or less) with a bainitic microstructure. However, tank cars are manufactured from steel plates which are considerably thicker than the sheet products that currently undergo TMCP. In 1995, a transient heat transfer model was developed to examine the range of possible TMCP processes for production of the desired bainitic microstructure in plate thicknesses appropriate for tank car construction. Results from the model suggest that the desired microstructure can be achieved through accelerated cooling of the material. Furthermore, a metallurgical study completed in 1996 indicates that the desired microstructure also can be achieved through the proper selection of alloy additives. These studies indicate that plate thicknesses of carbon steel with improved fracture and fatigue resistance can be manufactured. However, the economical manufacture of large quantities of such material has yet to be addressed, and is a topic for future research.

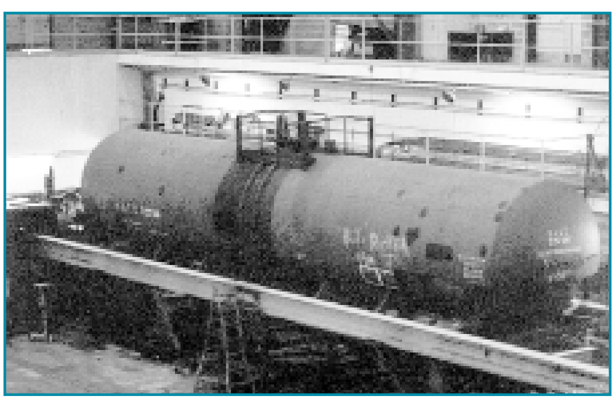
Damage Tolerant Design Methodology

Development of Damage Tolerant Tank Cars - Following investigations of two 1992 railroad accidents where hazardous materials were released from tank cars due to structural failures at pre-existing cracks, the National Transportation Safety

Board (NTSB) issued a special investigative report with recommendations to the FRA and industry. One of these recommendations was the development of a damage tolerance approach to the inspection and design requirements of tank cars. The damage tolerance approach was originally adopted by the U.S. Air Force for military aircraft and is now embraced by the airline industry for commercial transport airplane design. The basic concept behind damage tolerance is to ensure a high probability (through inspection and fracture-mechanics-based crack growth analyses) that critical components are inspected at some time between when a crack is first detectable and when it becomes large enough to cause failure of the component under expected service conditions. The damage tolerant analysis methodology might indicate some components where the design that promotes rapid flaw growth. In these cases, redesign or retrofitting might be attractive alternatives to short inspection intervals.

To facilitate the incorporation of damage tolerant design into the rail car industry, the FRA sponsored research to conduct stress analyses on two stub sill tank car designs, with and without head braces. Upon completion of these analyses, the major tank car builders initiated projects to develop finite element models for their own designs. Flaw growth rate predictions using the results of these stress analyses,were initiated. The results of these analyses will suggest both inspection intervals and design modifications for retrofit and/or future tank car designs. Similar analyses are planned for other critical areas of tank cars.

In 1994, the FRA, AAR, and RPI, initiated a joint program to complement the numerical analyses. To investigate the load environment experienced by a stub sill tank car in revenue service, full-scale tests were performed at TTC to estimate the in-service load environment. A car, provided by Union Tank Car Company, was instrumented by AAR/TTCI to measure coupler loads, car body strains, truck loads, and tank surge pressure. The accompanying photograph shows this tank car mounted in the simuloader facility at TTC. It was then equipped with a self-contained data collection system and a Global Positioning System and placed in service as an over-the-road test. Between August 1994 and March 1995, the tank car accumulated approximately 15,000 miles of in-service use.



The data accumulated in the over-the-road test were analyzed in several ways. Strain gage and coupler load data were analyzed using rainflow techniques which allows the user to accumulate the number of load cycles (peak-valley) experienced over a pre-set range. This methodology allows for great data compression, and provides results directly compatible with fatigue life models. It was found that significant fatigue damage was caused by large loads in the couplers in both the longitudinal and vertical directions.

Southwest Research Institute has been acting as an independent third-party program manager to provide oversight and guidance to this program while maintaining a confidential relationship with respect to the proprietary information of the tank car manufacturers. A report on their work is expected at the end of FY 1998. Future research needs in this area will be addressed upon review of this report.

Improved Inspection Systems - Under FRA regulations, tank car owners are required to employ periodic structural integrity inspections, including tank shell thickness tests and inspections of tank car welds. Detection of defects and other types of damage through non-destructive evaluations (NDE) can be difficult, especially when the tank cars are covered with a layer of insulation or lining material. By concentrating the required inspection to known areas of crack initiation, DOT's Research and Special Programs Administration and the FRA expect improvement in the reliability and efficiency of the inspection, and thereby a reduction in the inspection costs.

DOT authorizes five NDE methods which include dye penetrant, radiography, magnetic particle, ultrasonic, and optically-aided visual inspection. Other NDE methods may be used by DOT exemption. Rule HM175A/201 requires tank car repair facilities to document the sensitivity and reliability of the NDE methods used for the structural integrity inspections.

In light of the large number of welds on tank cars that need to be inspected to meet the structural integrity requirements of HM175A/201, the development of global NDE will significantly improve the probability of finding defects. Currently, acoustic emission evaluation of tank cars is providing not only information about the welds that must be inspected under the new requirements, but also about any defects on any part of the tank shell. Further evaluations of acoustic emission technologies as well as the development of other highly sensitive global NDE methods will increase the probability of finding defects.

A recommendation of the special investigative report written by the NTSB was to evaluate NDE methods which could be used in prescribed periodic inspection of all tank cars transporting hazardous materials. Acoustic emission was evaluated in 1996 as an NDE method to detect damage in welds and in the parent metal. Neutron radiography was examined as a method to determine subsurface weld strength. Another NDE activity will involve the development of a defect specimen library which would be useful for training and qualifying NDE technicians. In 1996, the AAR/TTCI began an investigation into the currently used methods of tank car inspection, with the ultimate goal of replacing or enhancing the prescribed hydrostatic testing of tank cars. The AAR/TTCI, in coordination with the AAR Tank Car Committee and with the RPI, selected four cars for testing. Baseline acoustic emission testing began in 1997.

NDE testing is currently underway. The railroad industry has provided tank cars that will serve as test subjects for the tests, as well as field support for the development of baseline inspection processes. A final report on this research is expected by the end of 1998. Once the baseline testing has been completed, at least five other non-destructive testing techniques will be used to evaluate the selected tank cars. The results of these tests will be compared with the baseline data to evaluate the effectiveness of the various NDE methods.

Shelf Coupler Height Mismatch Effects - Double-shelf couplers are designed to prevent uncoupling in an accident or incident involving severe braking. To prevent the release of hazardous materials due to the puncture of a tank head by an uncoupled coupler, double-shelf couplers are prescribed on all tank cars in hazardous materials service. However, it is suspected that the stiff double-shelf coupler design increases stresses in the stub sills, and has caused premature fatigue failure in certain tank cars. This project will examine the coupler-to-coupler interface and the draft-coupler assembly interface as a dynamic system to determine the forces resulting from the use of a double-shelf coupler. The study will recommend appropriate changes to the shelf coupler design to prevent further premature fatigue failures.

Heavy Gross Weight Tank Cars - Tank car builders and owners are currently submitting applications to the DOT for the use of rail cars with gross rail loads exceeding 286,000 lbs. Fatigue analyses on these designs are performed using FEEST-type loading spectra. However, the longitudinal and vertical coupler loads in these spectra should be scaled or modified to account for the increased gross weight of the cars. Currently, no regulatory requirements exist for the design of heavy gross weight cars. Before such a requirement may be considered or put into place, a study of appropriate scaling factors must be made.

The effect of increased gross weight on rail car loads and behavior are being determined through a review of past FRA research utilizing the Train Operation and Energy Simulator and by developing ADAMS computer models. Heavy gross weight tank cars might be more prone to buckling than current cars are. This issue will be investigated through finite element modeling. These studies will result in guidelines for tank car manufacturers to use when designing heavy gross weight rail cars.

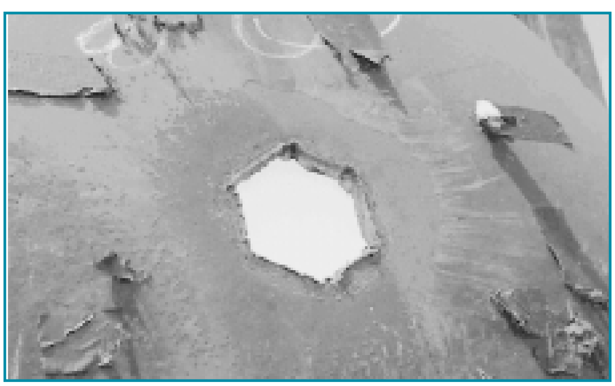
TANK CARS - FIELD PRODUCT REMOVAL

Placing Charge on Jacket

During derailment accidents, tank cars may become structurally compromised by dents, cracks, or punctures, and/or be subject to external heating. This compromise in structure, combined with increased internal pressure, can lead to catastrophic failure. The FRA tasked the AAR/TTCI's Hazardous Materials Training Center to research and develop safe, reliable operating procedures for field product removal.

RESEARCH STATUS

In this investigation, explosive charges were used to cut holes in tank cars to release internal pressure and to initiate a controlled release of product. Testing was performed on a sample tank car head and on four full-scale DOT112T340W tank cars. Various combinations of jacketing, insulation, and thermal protection materials were explosively cut.



Jacket Cut by Explosives

Mathematical modeling was used to determine the optimum vent and drain hole sizes, and to predict both vapor and liquid evacuation rates. Testing validated the mathematical models within acceptable limits.

KEY FINDINGS

As a result of this research program, *The Handbook for Vent and Burn Method of Field Product Removal* was developed. This handbook provides hazardous materials response professionals with a field guide of vent and burn procedures.

FUTURE RESEARCH

None. The vent and burn project is complete, having resulted in the publication of the referenced Handbook.

Foam Backed Charge on Tank

Water Draining from Tank